TIGER Radars Operations and Capability

April 2019

The TIGER radars are HF pulsed backscatter radars composed of 16 antennas in a main array that transmit on a narrow beam of approximately 3.25 degrees at half beam power, using phase offsets to electronically steer the beam direction. In the analogue Bruny and Unwin radars, beams can be steered to any one of 16 directions set via an analogue phasing matrix. In the Buckland Bark digital TIGER-3 radar, however, the phase offset for each transmitter (one per antenna) can be individually set, allowing the beam to be steered to any direction supported by the combined antenna pattern of the array. In normal operation beams are transmitted sequentially over the period of one minute depending on operational mode, thus sweeping out the radar Field of View (FoV). In the case of the older Bruny and Unwin radars 16 beams form a 52 degrees FoV, while the Buckland Park Radar can support a wider FoV of approximately 72 degrees using 22 beams. After each transmission the radar “listens” for received echoes that may be reflected from irregularities in the ionospheric sector being scanned, or even from the surface via reflection from the ionosphere (known as a hop). The returned scatter (echo) information is broken into time sampled “bins” that are normally 300usec, or equivalent to 45km, in length. For the Bruny and Unwin radars 75 bins are used setting the maximum range at ~3300km, alternatively in the Buckland Park radar 110 bins are generally used giving a range of ~5000km, although the radar has been operated quite effectively using 220 bins and a range of 10,00km. Combined the TIGER radars monitor a large swath of the ionosphere South of Australia and New Zealand, including a portion of the Antarctic Continent. The respective FoVs of the TIGER radars is shown in Figure 1. These have been deliberately overlapped to facilitate better velocity measurements of travelling ionospheric disturbances.

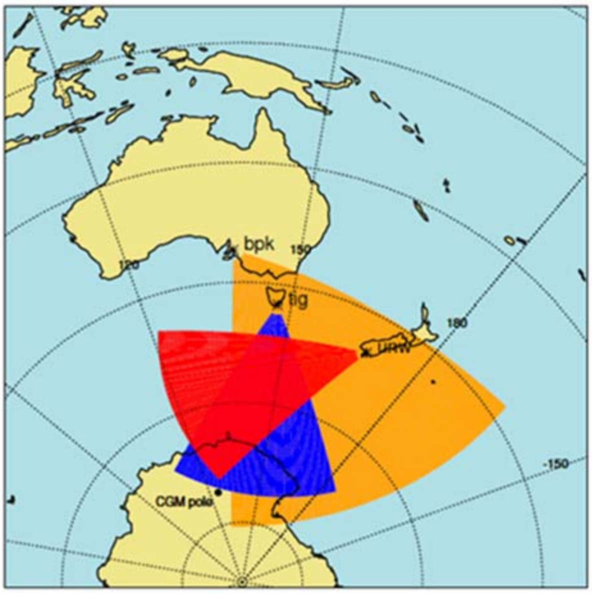


Figure 1. Fields of View of the TIGER Radars

Operation of the Bruny and Unwin radars

Each radar transmission consists of a predetermined a pseudo-random pulse sequence, typically containing eight, 300µs pulses, spaced at integer multiples of τ. Where a τ = 1.5msec is normally used. During each pulse sequence, the radar is switched into receive mode whenever not transmitting a pulse, up to the time that energy from the last transmission pulse would return as scatter from a target at extreme range. In the analogue radars, Bruny and Unwin, shown in Figure 2, the received signals from the antennas are mixed, after phasing, and passed to a single analogue HF receiver, where Inphase (I) Quadrature (Q) signals are sampled every 300µs. Information that sets out exactly when transmissions will occur and received samples are to be taken is known as the "timing sequence". A typical timing sequence used on the Bruny and Unwin radars is shown in Figure 3. To improve signal to noise, a timing sequence is repeated a number of times on each beam and the received data summed, creating a combined radar raw I & Q data set. Typically, the radars repeat 30 timing sequences over three seconds on each beam, before moving onto the next beam in the sweep. An entire sweep of 16 beams is conducted in one minute, including some overhead.

Once collected, raw I & Q received data is processed to produce SuperDARN standard files providing information on (i) Power; (ii) Doppler Velocity; and (iii) Doppler Spectral Width. Example data plots are shown in Figures 4 & 5. While in standard SuperDARN common time an entire sweep of the FoV is repeatedly conducted, at other discretionary times, the radar can be set to run using just a select number of beams, or even just a single beam. Finally, the radars have a second auxiliary (interferometer) array consisting of four antennas used for receive only that can be used to collect data for angle of arrival estimations. The location of the auxiliary array with respect to the main array is shown in Figure 6.

Figure 2: (a) Bruny Island Radar, Tasmania (b) Unwin Radar, near Invercargill, New Zealand

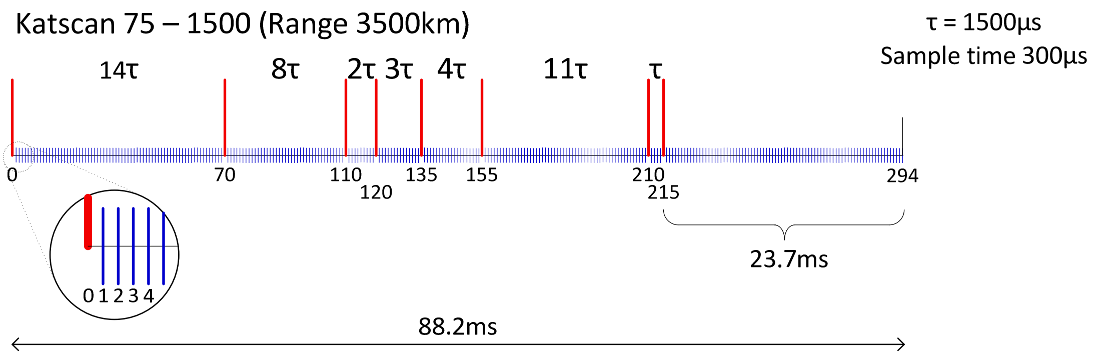


Figure 3: Typical SuperDARN common time Timing Sequence used on the Bruny and Unwin radars. Transmission pulses shown in red, with received signal samples shown in blue.

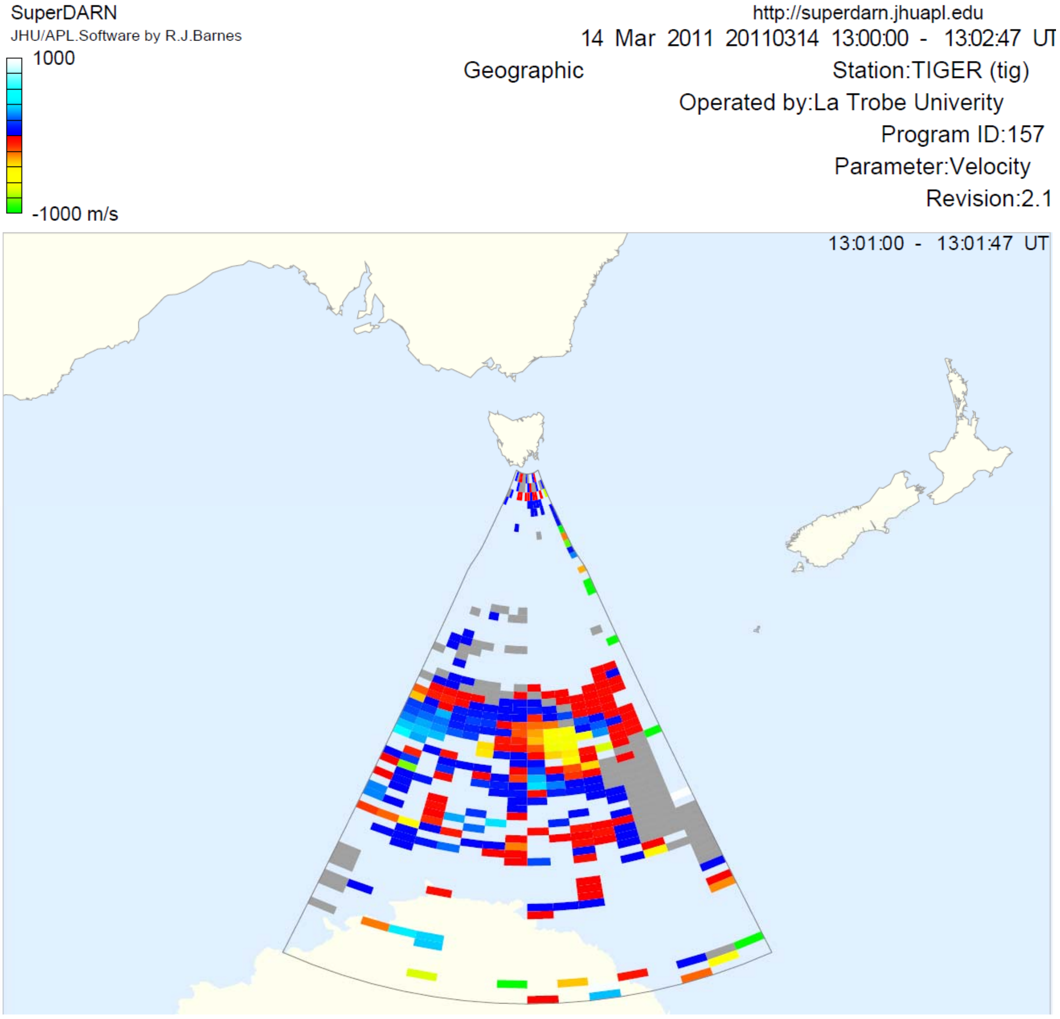


Figure 4: Typical single sweep fan plot from the Bruny Island radar

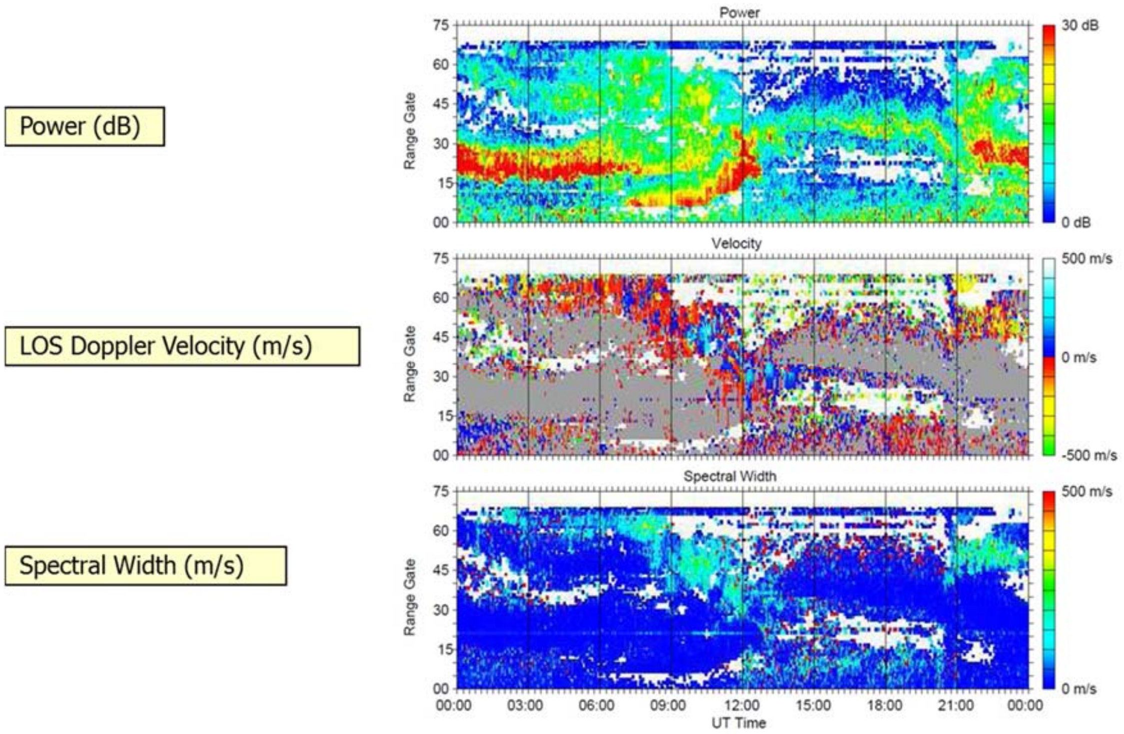


Figure 5: Typical 24hour single beam plots from the Bruny Island radar

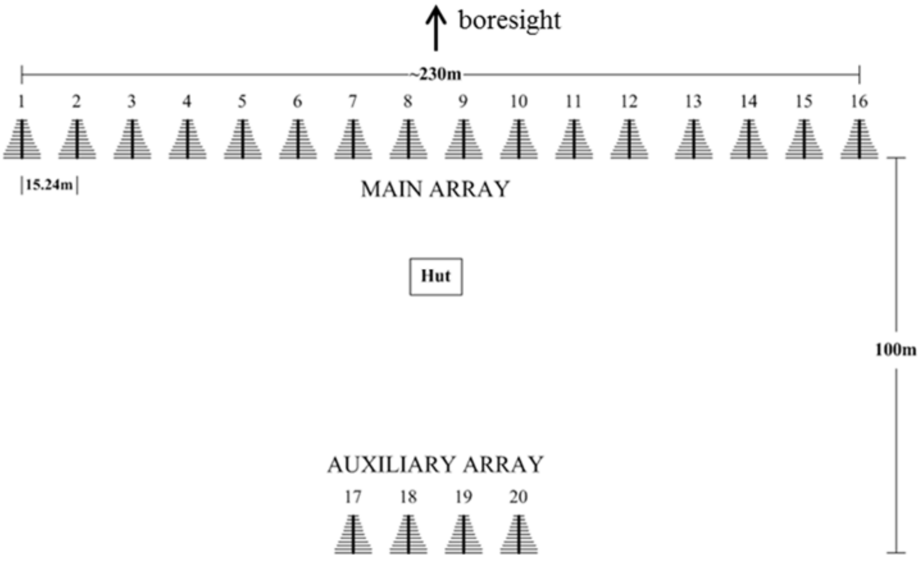


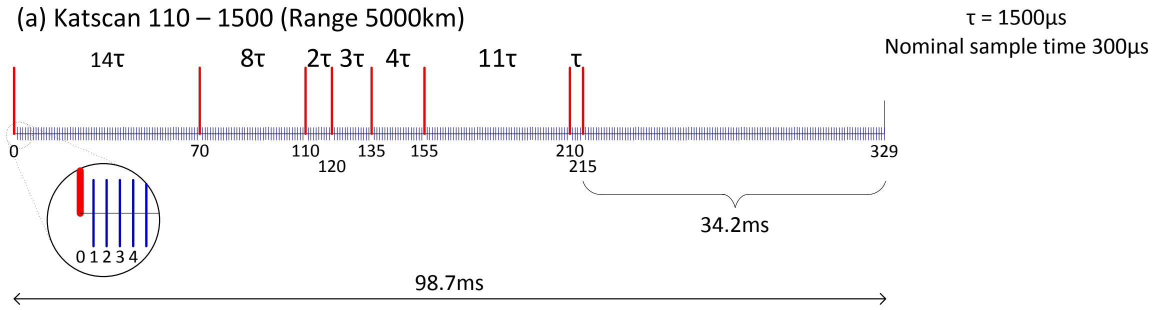
Figure 6. Site layout of Bruny and Unwin Radars

The Digital TIGER-3 Radar at Buckland Park

The third TIGER radar located a Buckland Park, South Australia, also known as TIGER-3, is a completely new digital radar design. While, it generally operates in a similar manner to the existing radars, it processes a vastly enhanced and expanded capability. The TIGER-3 architecture has 20 transceivers, one for each antenna. These “fully” digital transceivers have been built around Field Programmable Gate Array (FPGA) technology, each possessing full digital signal generation and control, coupled with high frequency RF sampling and hardware digital signal processing for the receive path, contained within. While a Main Computer runs the Radar Operating System (ROS), initialises and orchestrates accurately timed, coordinated, operations of the transceivers, each transceiver is a self-contained unit with all circuitry necessary for transmit and receive operation. This includes: power supply, RF signal generation; pulse shaping; automatic gain control; power amplification; high power switching; filtering; low noise amplification; RF sampling; in-phase and quadrature Doppler signal reception; and importantly for beamforming, accurate phase control. Performing phasing digitally in the transceiver eliminates the requirement for a separate phasing matrix, as well as, providing much finer beamforming control. During radar operation the receive data created at each transceiver is passed to the Main Computer where it is combined to create standard SuperDARN data sets, equivalent to those created by the analogue radars, although individual transceiver data can also be stored for special post processing.

The TIGER-3 design possesses a substantial performance improvement over the analogue radar design used at the Bruny and Unwin radars. Both through moving as much as possible of the transmit and receive paths into the digital domain and oversampling, coupled with SNR improvements in the analogue paths, and significantly higher power RF amplifier. This allows the Buckland Park radar to operate with greater range. Normally a range of 5000km is used, although it can be operated out to 10,000km. Typical SuperDARN common time Timing Sequences for these two scenarios are shown in Figure 7. Like the analogue radars a Timing Sequence is repeated for each beam, although less repetitions are required due to improved receiver sensitivity. When conducting an entire sweep of all 22 beams in one minute, approximately 2.8s are available to dwell on each beam, typically allowing 25 repetitions for a range of 5000km, and 20 for 10,000km.

(a) Katscan 110 – 1500 (Range 5000km)



(b) Katscan 220 – 1500 (Range 10,000km)

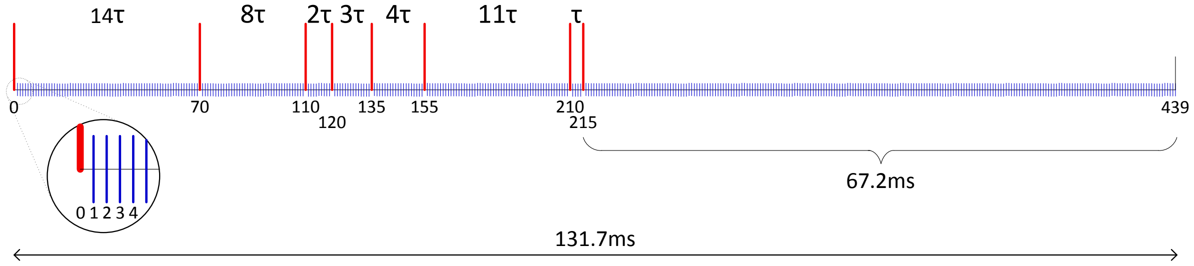


Figure 7: (a) Typical SuperDARN common time Timing Sequence used on the digital Buckland Park radar; (b) Timing Sequence extended for long range. Transmission pulses shown in red, with nominal

received signal samples shown in blue. While the nominal SuperDARN data set sample time of 300µs is shown, the Buckland Park radar can support considerable faster sample rates.

Buckland Park Radar Antennas and Site

The Buckland Park radar has been built using a twin-terminated folded-dipole (TTFD) antenna design. The design is an improvement to that used in a number of SuperDARN radars built over the last decade. This design enables array antennas to be placed closer together, thus producing a wider field of view than is possible with the Log Periodic antennas used on the Bruny and Unwin radar sites. Each antenna consists of two trapezoid loops of 12-gauge wire strung up between 17m high flag poles, spaced 14 m apart, using 3 horizontal lengths of Kevlar cable. Behind the antennas is a corner reflector running the length of the entire array which directs power forward. Figure 8 shows the construction of the front antenna on the Buckland Park site, with partial views of the main and rear arrays in the background, while schematic diagrams of the Buckland Park antenna design, are shown for front, side and oblique views in Figures 9a, 9b and 9c respectively.

Figure 8. Buckland Park TTFD antenna construction – front antenna view.

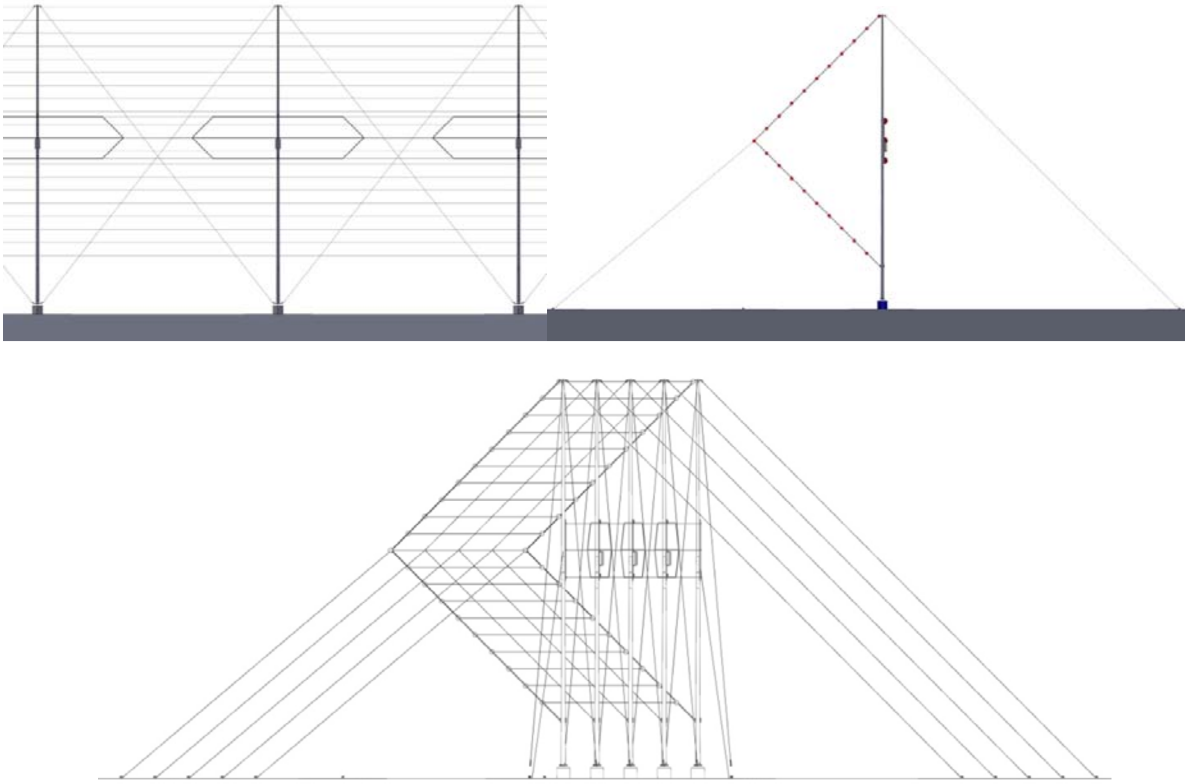


Figure 9. Schematic diagram of the Buckland Park twin-terminated folded-dipole antenna array showing the (a) front view; (b) side view, and (c) oblique view.

The Buckland Park antenna design has been altered, from that used at other SuperDARN radars, to improve performance and reduce the variation in the voltage standing wave ratio. As the impendence of the antenna elements varies across the array, particularly at the ends of the array, special antenna matching filters have been designed to match impedances between each antenna and transceiver. These were developed following the measurement of antenna characteristics on site, and then installed in housings at the feed point of each antenna, as shown in Figure 10. Similar radars typically use iron core baluns for matching. These provide very good matching over a narrow band, but severely restrict performance for wide-band operation. The result at Buckland Park is a reasonably consistent match for all antennas across the frequency band 9 – 16.5MHz, as illustrated by the on-site VSWR measurement in Figure 11. Further while is often assumed that all transmitters are transmitting with the same power, in practice with the existing radars, the power output driving each antenna can vary by 10% or more, impacting the quality of the beam forming. In the TIGER-3 design digital power monitoring and control ensures that all transceivers transmit with less than a 3% difference in power. All these changes ensure that the transmitted beam is as narrow as possible.

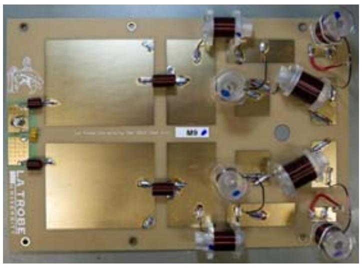


Figure10(a) – Matching filter implementation

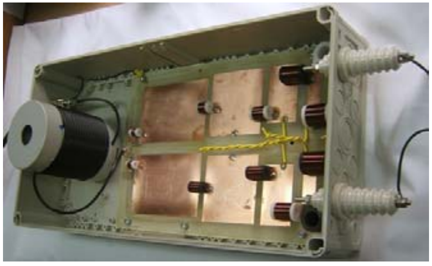


Figure 10(b) – Filter housing with air core balun

Figure10 (c) – Matching filters installed on site

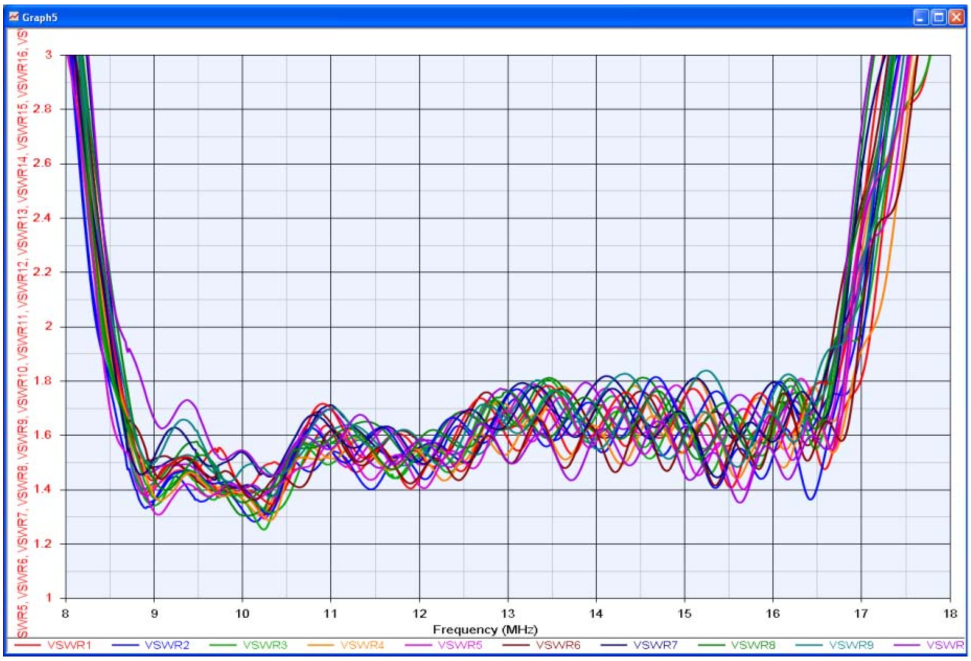


Figure 11. VSWR measurements, for all main array antennas with matching system installed.

In the other TIGER and SuperDARN radars the Angle of Arrival (AoA) cannot be determined precisely due to the 2π ambiguity (or AoA aliasing effect) that results from the rear array being placed more than one wavelength behind the main array. The assumption is made that that only a restricted range of propagation modes can return scatter to the radar due to their limited range, and thus the range of the returned signal is as part of the AoA estimation. With the greatly enhanced range of the Buckland Park radar, and hence propagation modes supported, a more precise AoA measurement is required. This is facilitated by moving one of the rear array antennas to the front the main array. The Buckland Park radar footprint thus consists of a single antenna, in front of a 16-element main array, with a three-element rear array. Provided that the difference in distances between the front antenna and the main array, and the main array and the rear array is less than the smallest wavelength used by the radar, the AoA can be determined without ambiguity. The site layout of the Buckland Park footprint is shown in Figure 12. With a ground view showing all three sets of antennas in Figure 13.

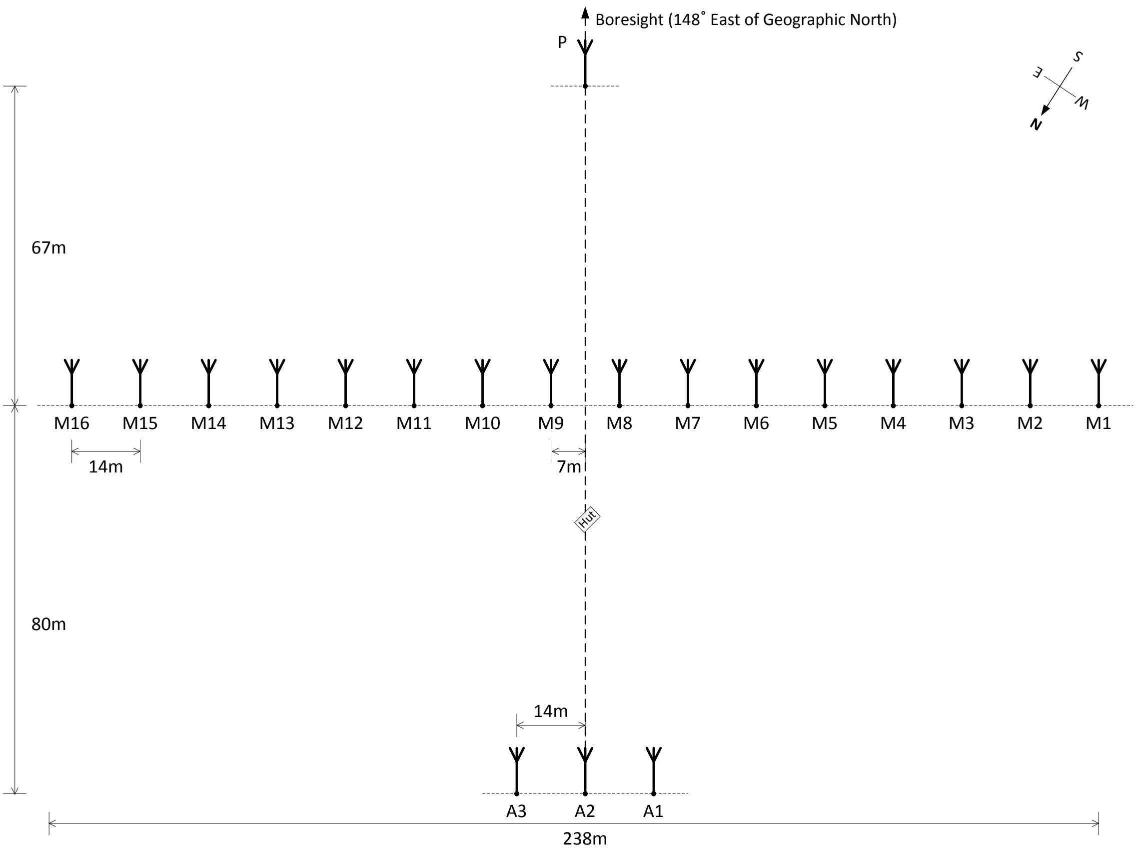


Figure 12. Buckland Park Site Layout

Figure 13: The Buckland Park Radar, looking North-East

Operational Parameters of the TIGER-3 Radar Design at Buckland Park

Each TIGER-3 transceiver is fully independent, capable of generating all the necessary signals for transmission and reception between 9 and 16.5MHz. Although, for sensible radar operation coordination between the transceivers is required, which is the responsibility of the Main Computer. However, as each transceiver possesses two independent transmit/receive channels, including those attached to the Auxiliary antennas, it is possible to operate a range of different virtual radars using the same physical antenna array. The only caveats are as follows. 1. A transceiver cannot receive while it is transmitting. That is physically blocked, with receive signals digitally zeroed. 2. The peak amplitude of the output transmit signal combined from the two channels must not exceed the maximum input level of the power amplifier chain. Over-voltage protection circuitry has been included, so no damage will occur, just distortion in the output signal. Thus, for example, it is possible for the main array to be split into sub arrays; or the auxiliary antennas to operate separately from the main array; or the second channels used as separate or combined listing posts.

Typically, during SuperDARN common time, Channel A in each transceiver is dedicated to producing standard SuperDARN data. While Channel B is free for discretionary campaigns, provided that they fit in with the common time transmit timing sequence. During discretionary time periods the entire radar can be used for whatever investigation is deemed appropriate, with no requirement to use SuperDARN timing sequences. Subject to a maximum full power transmission duty cycle of 5.5%.

On a per transceiver basis, for each of the two channels, the following parameters can be individually controlled.

- Frequency (9 – 16.5MHz, at increments of ~30mHz, and subject to ACMA licence)
- Phase (in degrees, at increments of 10^{-7} degrees)
- Transmission amplitude (where zero amplitude = Rx only)
- Pulse width (from 100us up, provided the full power duty cycle does not exceeded 5.5%)
- Full Timing Sequence control, including: number of transmission pulses; the pulse pattern and timing; receive sampling timing. Basically, full control, subject to duty cycle limit and an upper limit of sampling rate (~250 ks/s)
- The bandwidth of each narrow band receiver can be tuned between 3-10kHz

As well as the two narrow band receivers, each transceiver also contains a wide band digital spectrum analyser, which updates every 100ms and can be used to continually monitor local RF sources. For SuperDARN operations is used as a clear frequency search when determining which frequencies to operate at. Although in a passive radar context it could be used to determine available sources of opportunity and hence which frequencies are best to use at any given time. Finally, each transceiver, continually every 100ms, sends housekeeping and real-time monitoring data (including, Core Voltage, Peak RF Voltage) back to the Main Computer enabling immediate assessment of the heath of each transceiver.

Further Specification and Operations Information

Further specifications and operational information for the TIGER-3 radar design operated at Buckland Park are provided below.

- Transmission power/RF emissions – typically 1kW per transceiver, or 16kW when transmitting on the 16-antenna main array.
- Receiver sensitivity - Rx Noise Figure 1.9dB (below atmospheric noise), range (capable of at least 10,000km, SNR – up to 70dB from ionospheric echoes, while transmitting ~16kW peak pulse @ 3% duty cycle.
- Single beam Field of View – typically 3.25 degrees in azimuth and a range of 5,000km.
- Instrument Field of Regard - typically operated with 72 degrees in azimuth and a range of 5,000km, elevation varies with frequency, typically 10 – 60 degrees.
- Operating times, weather/environment limitations – no limitations, operates remotely 24/7.
- Redundancy – operates independently on mission task set. New missions can be uploaded remotely. No daily intervention required.
- Reliability, Availability and Maintainability estimates – currently ~96%, main issue is losing mains power on-site. A UPS is used for main Computer, but is not sufficient to run radar. The nature of scientific work currently conducted has not been deemed essential for a full remote backup supply. This could be installed in the future if appropriate.
- Maintenance – Electronics system and antenna check once per year, by electronic technician at Senior Technical Officer level.
- Spare parts – no consumables as such, although spare modules are kept on site for easy replacement in case of failure.
- Standards compliance – ACMA licence for operating at HF frequencies on a non-interference basis. Emissions standard: CISPR32
- Mission/control system
    - Remotely operated – yes, operates independently on mission task set. New missions can be uploaded remotely. No daily intervention required.
    - Can operate with multiple sensing modes at same time – yes, as discussed previously, each transceiver has two independent channels, and a wide band spectrum analyser. Sections of the radar hardware can also be assigned different tasks.
    - Can Mission/control system be update/tasked remotely – yes, and campaign tasks could even be remotely set via another system. Full remote reconfigurability - software updates and even new digital hardware (FPGA) designs can be installed remotely.
    - Personnel – technical officer level with modest training required to oversee operation, average one day a week.
    - Status and faults – yes, there is a self-monitoring and reporting capability.
    - Can faults be remotely fixed/cleared – mostly, operating software can be changed/updated remotely, each transceiver and the Main Computer can be remotely reset, and transceivers with significant faults can be remotely taken offline so as to not disrupt the remaining system. A back-up main computer is

maintained on site and can be swapped over remotely, however, while spare transceivers are kept on site these need to be physically swapped over.

Should it be desired to create another TIGER-3 type HF radar at another site, the following information is relevant.

- location considerations – a TIGER-3 type HF radar typically requires a flat site around 300m x 200m (depending on array configuration). It can be located in a remote site (many SD radars are), boresight and FoV are set by antenna placement, informed by overall mission.
- infrastructure requirements – equipment hut/enclosure, mains power (or equivalent), communications link of 5 Mbps, local storage on Main Computer 10TB.
- Ambient operating range – have operated system in range 0-45 degrees Celsius without special cooling or heating, although some A/C or heating in hut for extremes is recommended.
- Supply chains/cost – (i) build of complete TIGER-3 type electronic hardware consisting of 20 transceivers + 5 spares, 12 months @ $0.75M - $1M; (ii) complete system with 20 TTFD antennas, 18 months @ $3M, assuming easily accessible site available.

Buckland Park Radar Example Results

Provided below are selected examples of the Buckland Park radar’s ionospheric/space weather observations. These examples illustrate how essential the characteristics of, long range, a wide field of view, and frequency agility, are for the radar to detect the wide assortment of ionospheric disturbances and space weather that can occur down range of the radar at any given time.

Figure 14 shows the ionospheric and ground backscatter echoes observed over the field of view of the Buckland Park radar on 23 September 2014, 10:00-10:28 UT, at 7 different frequencies. Echoes are colour coded according to the Doppler velocity measured by the radar, with positive velocities indicating motion towards the radar. Large amounts of backscatter were detected at all frequencies, demonstrating the strong performance of the impedance matching system, which enables the normally narrow band TTFD antennas to act as wide band antennas across 9-16.5 MHz.

Ionospheric plasma convection velocities ranging from about 100-500 m/s were observed on the west side of the field of view at ranges up to 4000 km from the radar site (coloured green/blue). This convection is indicative of ionospheric electric fields and magnetic-field aligned currents generated in the magnetosphere. The observed plasma flow is consistent with the expected strong anti-sunward convection at this time of day. Low Doppler velocity ground backscatter (brown), corresponds to signals reflecting from the ionosphere and scattering from the ground or the sea. These signals, valuable in determining the detailed state of the ionosphere and sea state, were detected at all frequencies during this interval. As the frequency increases, signals undergo less refraction in the ionosphere and so the ground backscatter is observed at increasingly greater ranges from the radar. As demonstrated by physicists at La Trobe University, the ranges achieved by signals of different frequencies can be used to provide real-time frequency advice to users of HF radio communications. The increased extent of ground backscatter, at times detectable at ranges up to 5000km – an improvement of approximately 50% on the previous radar technology - also demonstrates the radar's potential as an instrument for monitoring sea-state conditions over the Southern Ocean, a region unobservable by any other ground-based meteorological instrument.

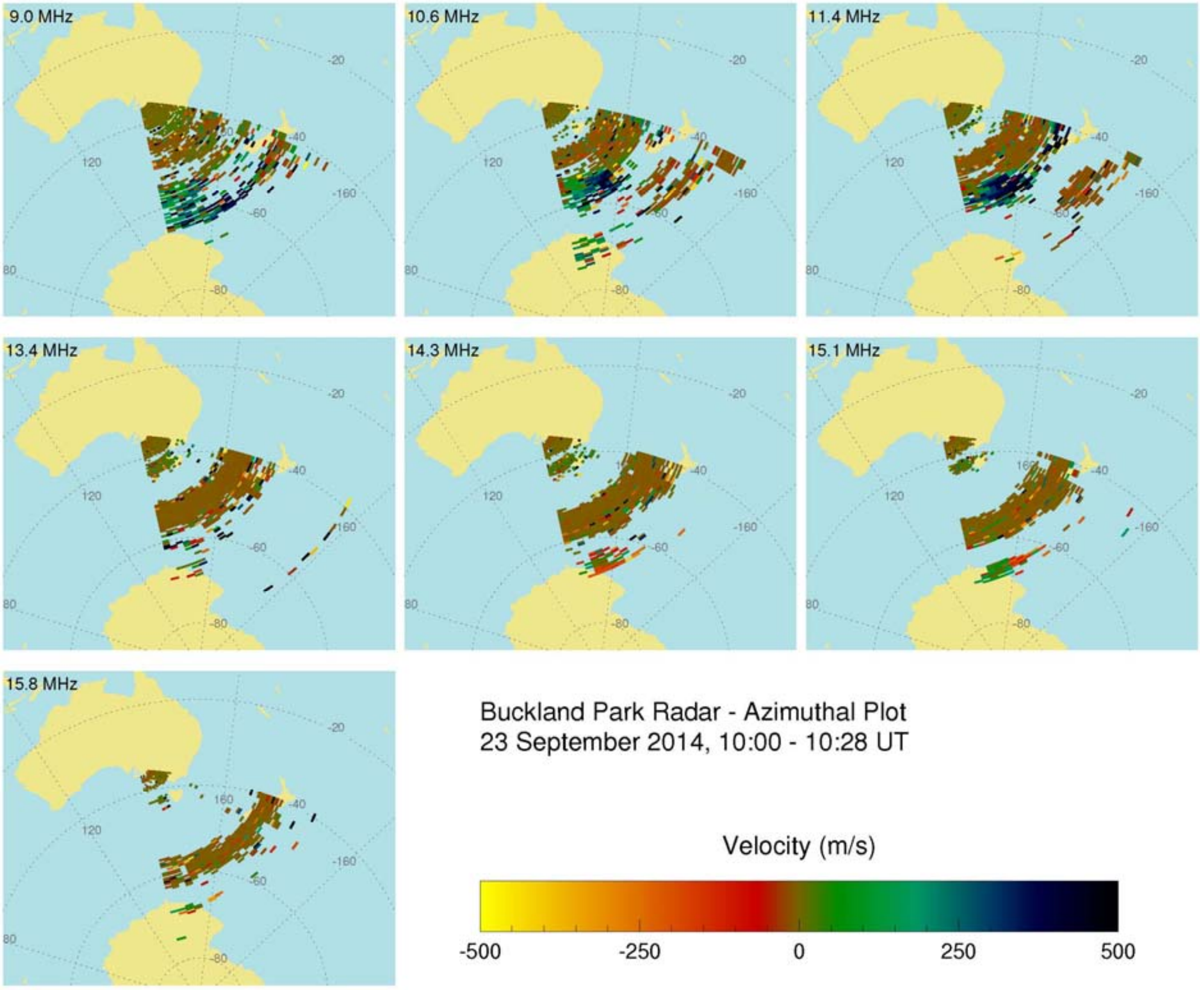


Figure 14: Ionospheric and ground backscatter echoes observed over the field of view of the Buckland Park radar on 23 September 2014, 10:00-10:28 UT, at 7 different frequencies.

Figure 15 is a typical whole-day range-time-power plot, in this case a poleward beam #7 (out of 22 beams). Ground scatter from the distant sea via multiple reflections from the ionospheric F region are clearly visible. Also visible during local night are backscatter reflections direct from the F region ionosphere. Meteor echoes occur at short range.

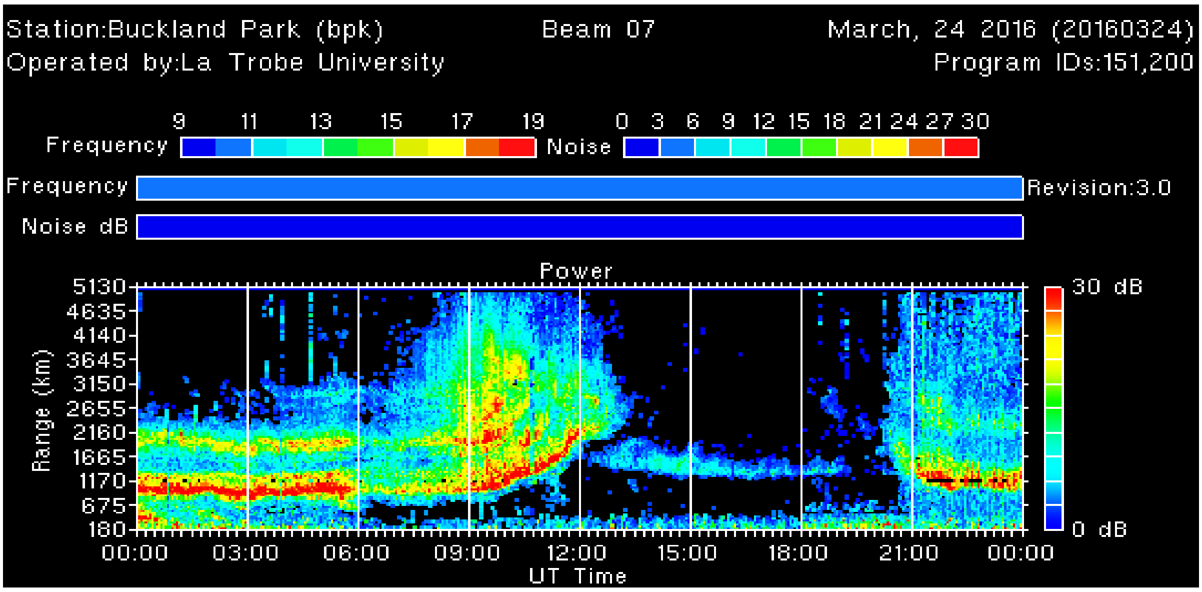


Figure 15: Range-time-power plot for beam 7, looking poleward, from the Buckland Park radar on 24 March, 2016. Frequency is in MHz.

Figure 16 is a 24 hour single beam power and Doppler velocity plot, this time looking Westward over New Zealand. Gravity waves most clearly show up at night time between 9:00 and about 20:00 UT. Considerable meteor scatter is observed at close range during the day.

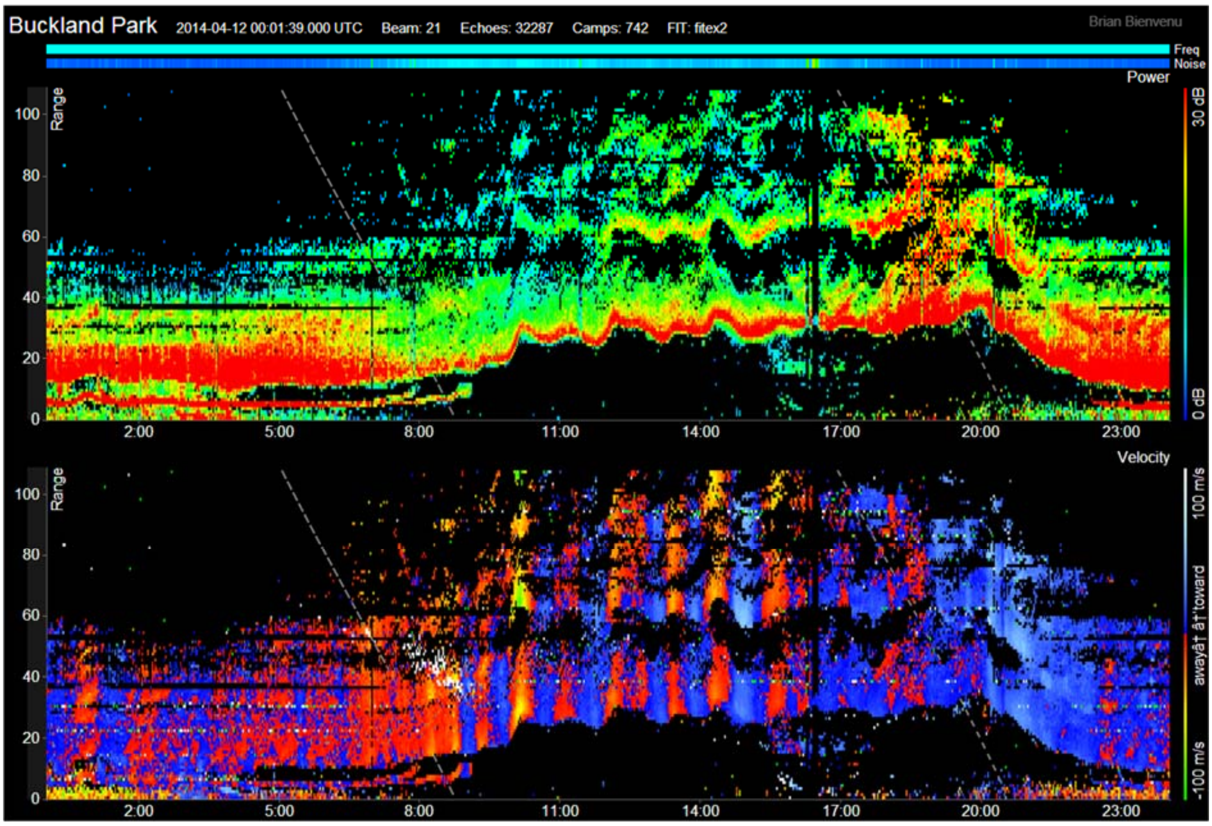


Figure 16: 24hr Range-time-power and Doppler velocity plot for beam 21, look Westward over New Zealand, from the Buckland Park radar on 12 March, 2014.

Figure 17 very clearly illustrates the timing sequence for long range operation, matched with the corresponding raw I & Q data recieved, and derived power plot. In this case two hops of sea scatter are being observed, with path lengths of 2790km and 7230km. These returns clearly show up in response to each transmission pulse. For this campaign a longer τ of 2.4ms was used to improve the Doppler velocity measurement.

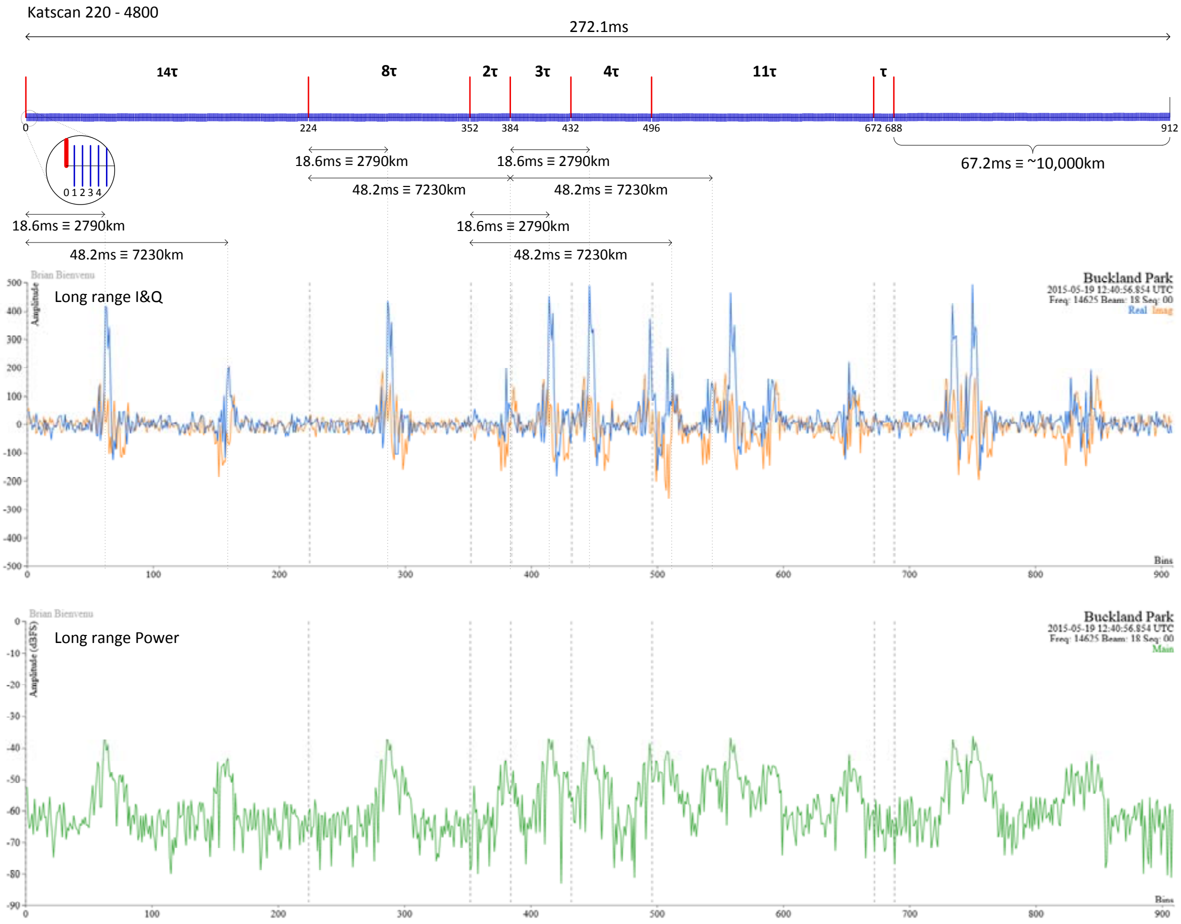


Figure 17: Buckland Park long range timing sequence with corresponding raw I & Q data and derived power plot. Transmission pulses shown in red, with received signal samples shown in blue.

Figure 18 is another example of long range operation, this time showing power returns at four different frequencies. This clearly shows the range of the instrument across the Antarctic continent and Southern Pacific Ocean to the tip of South America. The wide band capability of the instrument is also demonstrated by good long range returns at each frequency. This illustrate that the radar is observe how the propagation conditions, including position and number of hops, changes with frequency.

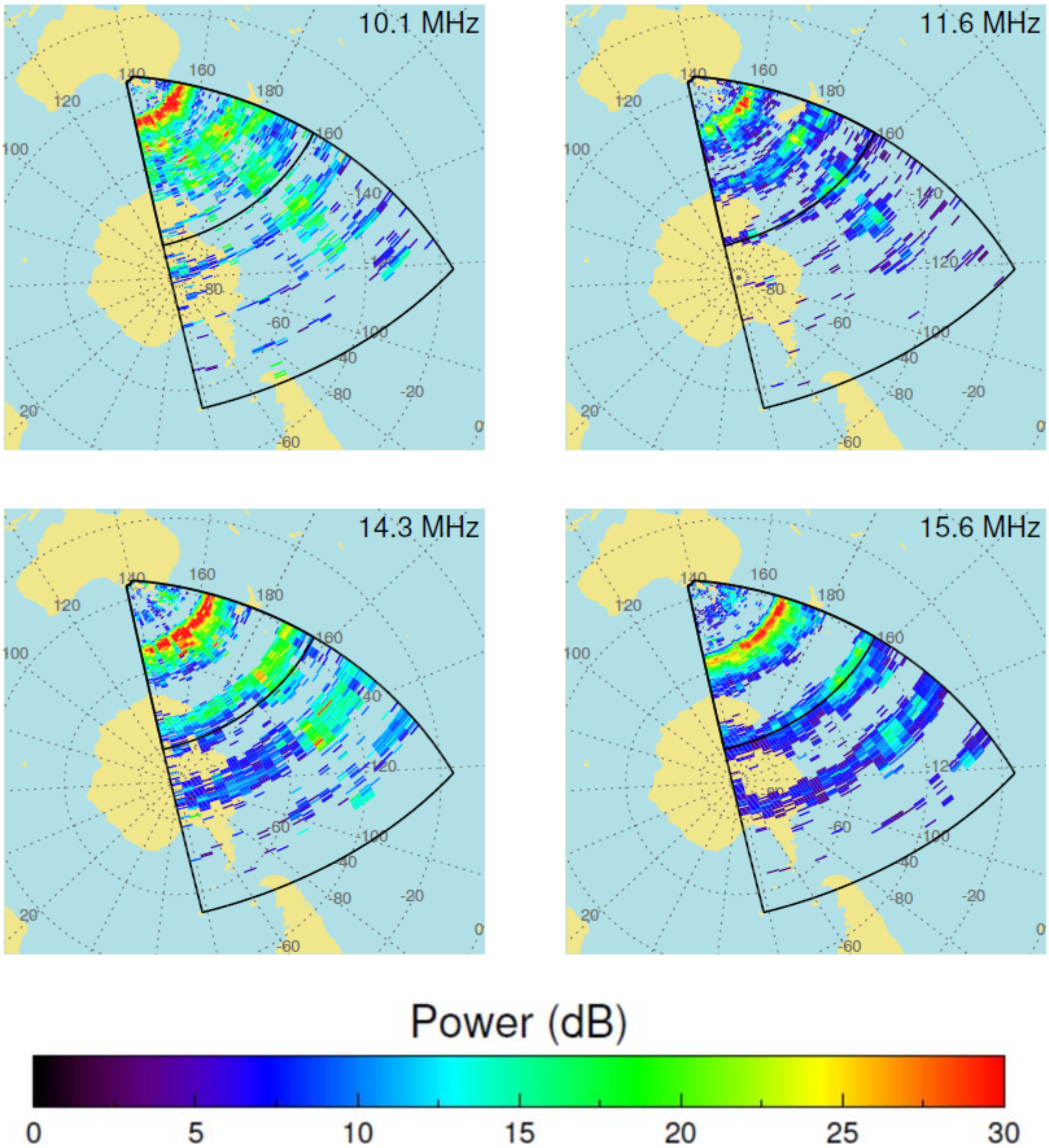


Figure 18: Long range field of view power returns of the Buckland Park radar 29 December 2014, 10:00 – 10:24 UT, at 4 different frequencies.